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The impact of the rebound effect of the use of first generation biofuels in the EU on greenhouse gas emissions: A critical review

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ABSTRACT

An important objective of the mandated blending of biofuel in conventional gasoline and diesel in the EU is reducing greenhouse gas (GHG) emissions. An important assumption thereby is that biofuels replace the production and consumption of oil. However, recent literature challenges this assumption, because an increased use of biofuels will lower oil prices and therefore result in increase crude oil consumption. This so-called rebound effect offsets the expected GHG emission saving effects of using biofuels. A review of eight studies, mainly on current and future US biofuel policies, provides insights in the current state of research into this topic, showing a wide range of values of the rebound effect of biofuel use, depending among others on the biofuel policy, the applied method and the model parameter assumptions. Generally, estimated rebound effects are negative in the country where biofuel use is being promoted (i.e. the use of 1 unit of biofuel reduces oil consumption by less than 1 unit; units on energy basis). The rebound effects in other countries are always positive (biofuel use reduces oil consumption by less than 1 unit so the total fuel consumption is increasing). The net global rebound effect is usually positive, which means that GHG emissions savings are not achieved as much as usually is assumed, or emissions may even increase. Own estimations with the global MAGNET computable general equilibrium model indicate a global rebound effect of the 10% biofuel blend mandate in the EU in the year 2020 of 22–30% (i.e. the use of 1 unit of biofuel reduces global oil consumption by 0.78–0.70 units). This means that GHG emissions will not be reduced as much as usually is assumed, or may even increase. These results show that rebound effects can significantly lower the effectiveness of biofuel policies in reducing GHG emissions.

Contents

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1. Introduction

The production and use of biofuels for road transport is an important component of the energy policies of many countries. By now more than fifty countries have implemented promoting policies, such as blending targets and financial incentives, use and many other countries are currently implementing or considering similar policies [1,2]. As a result of these policies global biofuel production increased from 16 billion litres in 2000 to more than 100 billion litres in 2010 and is expected to triple between 2010 and 2035 [2,3].

Important objectives of biofuel supporting policies are, among others, to reduce the dependency on fossil oil imports, to increase energy security, and to increase resilience against fossil oil price fluctuations. Another important rationale, especially in the EU, is the reduction of greenhouse gas (GHG) emissions [4]. The Renewable Energy Directive (RED) requires that all member states of EU achieve a 10% share of renewable energy by 2020 for all land transport [4]. The RED also requires that the GHG emission savings of biofuels must be at least 35% compared to fossil fuels and shall increase to at least 50% by 2017 and 60% by 2018 for biofuels produced in new installations [4]. The 10% target of the RED is expected to be met mainly by first-generation biofuels, such as ethanol made from conventional sugar and starch crops, and biodiesel produced from vegetable oils [5]. This may change as various proposals have been and are discussed to limit the use of first-generation biofuels and simultaneously encourage the contribution of biofuels from other feedstock, such as lignocellulose biomass [6].

A conventional (attributional) Life Cycle Assessments (LCA) method is commonly used to calculate the GHG emissions reduction as a consequence of biofuels production. Also the European Commission is using this method to asses GHG emissions of biofuels [4,7]. An important limitation of this method and therefore also RED GHG emission calculations is that it only considers the emission from the production and use of biofuels; market and economic effects of EU's biofuel policy are often ignored [8–10]. Missed effects are, among others, Indirect Land Use Change (ILUC) and the rebound effect.[1] ILUC is the unintended change of land use around the world that is induced by the expansion of croplands for biofuel production in response to the increased demand for biofuels. ILUC can result in GHG emissions if natural vegetation (forestry, grasslands) is converted into less carbon rich vegetation types, i.e. when the carbon stored in these vegetation types is released. The rebound effect is the effect that an increased use of biofuels reduces oil demand, which in turn results in, among others, a decrease of the price of oil. This oil price decrease leads to higher demand for oil, which causes oil consumption to decrease less than the increase in biofuel use (on energy content basis).

During the past years the impact of ILUC on GHG emissions has received a lot of attention, yet not the rebound effect. The aim of this study is to show the relationship between biofuel policies and GHG emissions by pointing at fuel market dynamics resulting in rebound effects and to indicate the importance of rebound effects, which are missed in most LCA studies. In addition we add to examples in available literature by quantifying rebound effects of biofuels for transport in the EU 27 and its consequences for (expected) GHG emission savings.

The structure of the article is as follows. First, the rebound effect measure is defined (Section 2). Second, an overview of key literature investigating the rebound effect of biofuels is given, emphasising on major features of the studies such as the applied methods, scenarios, model assumptions, geographical scope and time frame (Section 3). Specific attention is paid to, among others, the price elasticity of oil demand and supply, the role of the Organisation of the Petroleum Exporting Countries (OPEC) cartel of oil producers and how various policy incentives (biofuel blending mandate, biofuel tax exemptions) affect consumer and producer behaviour on the short and long terms. We complement the review by own calculations of the rebound effect of biofuel use in the EU with the MAGNET computable general equilibrium model (Section 4). Finally, the impact of the rebound effect of biofuel use in the EU on GHG emissions is calculated based on the range of rebound effects predicted by MAGNET and the range found in the literature, taking into account the specific characteristics of biofuel supporting policies in the EU and also the emissions of biofuel production and ILUC (Section 5). In Section 6, conclusions and policy implications are discussed.

2. The rebound effect concept

The underlying notion of the rebound effect of biofuel is that the use of biofuels has economic implications that affect the consumption and price of oil and that, as a result, an increase in biofuel use is not by definition followed by an equal decrease in oil consumption (on energy basis). Fig. 1 represents the basic mechanisms that cause the rebound effect of biofuel use in case of mandatory blending of biofuel with gasoline and considering trade of gasoline fuel. This figure is based on Drabik and De Gorter [16]. Note that in the remaining of this report we do not make distinction between oil use and use of gasoline and diesel, as oil refining is typically optimised towards production of gasoline and diesel. More complex demand and supply correlations are considered in the reviewed studies, as further discussed in Section 3.

In Fig. 1 two regions are distinguished, Home (Ho) and Rest of the World (ROW). The home country is assumed to be a net importer of gasoline, as is the case for the US and the EU. Without a biofuel blend mandate the price of gasoline (P_{Go}) is where the demand curve of fuel (D_{Ho}) crosses the total gasoline supply curve ($S_{HoTo\ G}$). This total gasoline supply curve is the sum of the supply curve of gasoline in the home region ($S_{Ho\ G}$) and the excess supply in the ROW (defined as the $S_{ROW\ G}$–$D_{ROW\ G}$). The implementation of a binding biofuel blend mandate implicitly results in a demand curve for biofuel in the Home region ($D_{Ho\ B}$). The production of biofuel in the Home region is represented by the supply curve

[1] The rebound effect of biofuel use is also known as Indirect Fuel Use Change (IFUC; e.g. Rajagopal et al. [11] and Hochman et al. [12]) or Indirect Energy Use Changes (IEUC; [13]), although definitions differ sometimes from the ones used in this paper. De Gorter and colleagues [14,15] use the term Indirect Output Use Change (IOUC) for the same phenomenon. Also the terms carbon leakage or fuel market leakage effect is sometimes used.

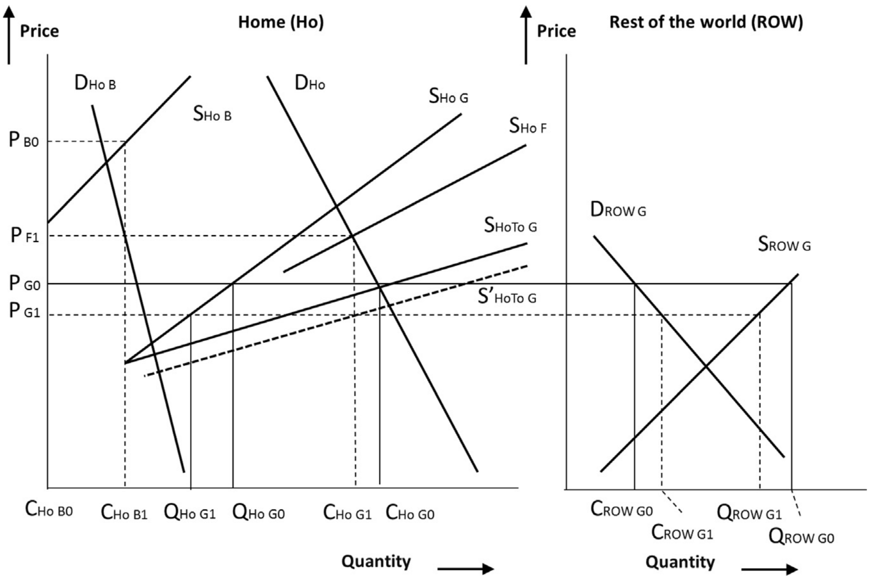

Fig. 1. An overview of the impact of a biofuel blend mandate on gasoline demand and supply. The dotted lines indicate the prices and volumes; the dashed line shows the impact of biofuel use on gasoline supply in the Home region (based on Drabik and De Gorter, [16]).

$S_{\text{Ho B}}$ and blending of the biofuel with gasoline results in a new supply curve of fuel in the Home region ($S_{\text{Ho F}}$). The intersection of the domestic fuel demand curve (D_{Ho}) and the new supply curve determines the new equilibrium price of fuel (P_{F1}), which is typically higher than P_{Go}. The amount of biofuel produced and consumed is the intersection of the equilibrium price of fuel and the biofuel supply curve ($C_{\text{Ho B1}}$). The production of biofuel effectively results in a downward shift of the Home's total gasoline supply curve ($S'_{\text{HoTo G}}$). The new equilibrium (world) price of gasoline (P_{G1}) is realised when consumption of gasoline is $C_{\text{Ho G1}}$, which is less than before the biofuel mandate was introduced as biofuels replace gasoline in the fuel mix With the new equilibrium price P_{G1} for gasoline, gasoline production in the Home region and in the rest of the world decreases to, respectively, $Q_{\text{Ho G1}}$ and $Q_{\text{RoW G1.}}$ Consumption of gasoline in the rest of the world increases (to $C_{\text{ROW G1}}$) and consumption of gasoline in the Home region may increase or decrease, depending on the price–supply and price–demand relationships depicted in Fig. 1. In this study we derived from Fig. 1 the following definitions of the rebound effect of biofuel use:

Rebound effect Home

$$\text{RE}_{\text{Ho}} = (C_{\text{Ho B1}} - C_{\text{Ho B0}} + C_{\text{Ho G1}} - C_{\text{Ho G0}})100/(C_{\text{Ho B1}} - C_{\text{Ho B0}})$$

Rebound effect ROW

$$\text{RE}_{\text{ROW}} = (C_{\text{ROW G1}} - C_{\text{ROW G0}})100/(C_{\text{Ho B1}} - C_{\text{Ho B0}})$$

Rebound effect World (sum of RE_{Ho} and RE_{ROW})

$$\text{RE}_{\text{WRLD}} = (C_{\text{Ho B1}} - C_{\text{Ho B0}} + C_{\text{ROW G1}} - C_{\text{ROW G0}} + C_{\text{Ho G1}} - C_{\text{Ho G0}})100/(C_{\text{Ho B1}} - C_{\text{Ho B0}})$$

where RE is the Rebound Effect (%), $C_{\text{Ho B0}}$ the Biofuel consumption in the Home region without biofuel policies in the Home region, $C_{\text{Ho B1}}$ the Biofuel consumption in the Home region with biofuel policies in the Home region, $C_{\text{Ho G0}}$ the Gasoline consumption in the Home region without biofuel policies in the Home region, $C_{\text{Ho G1}}$ the Gasoline consumption with biofuel policies in the Home region, $C_{\text{ROW G0}}$ the Gasoline consumption in the ROW region without biofuel policies in the Home region and $C_{\text{ROW G1}}$ the Gasoline consumption in the ROW region with biofuel policies in the Home region.

A RE_{WRLD} of 25% and -25% means that the use of 1 energetic unit (Joule) of biofuels in the Home region decreases the worldwide consumption of gasoline by 0.75 and 1.25 units, respectively (consumption quantities are expressed in energy units). In the framework above and in this paper, we ignore the use of oil based fuels for the production of biofuels, because the use of gasoline and oil for the production of biofuels is limited to less than 5% of the energy content of the first-generation biofuels that are currently used [7].

3. Review of studies on the rebound effect of biofuels

This section summarises approaches and outcomes of studies that deal with rebound effects of biofuel policies. First, we provide an overview of key features of the eight reviewed studies (Section 3.1). Second, the results of these studies are presented in terms of the rebound effect in the Home region, in the ROW region and globally (Section 3.2). This is followed by a more detailed evaluation of the crucial factors and assumptions that determine the rebound effect of biofuel use in each of the respective studies (Sections 3.3–3.8).

3.1. Key characteristics of studies on the rebound effect of biofuels

We searched several scientific literature databases and internet databases and found eight studies that explicitly deal with the rebound effects of biofuels. Table 1 shows the key characteristics of these eight studies. Five of the eight studies focus on the rebound effect of the Renewable Fuel Standard (RFS) 2 biofuel policy in the US. Two studies consider global biofuel policies and only one study specifically focuses on the EU. Five studies are based on Partial Equilibrium (PE) models, of which one is based on a Cartel of Nations (CON) PE model that specifically considers the OPEC cartel of oil producers. Two studies are based on Computable General Equilibrium (CGE) models. The timeframes considered vary between 2009 (simulations based on observed data) and 2022, which is the end year of the RFS2 policy. In most studies, the impact of various policy measures (biofuel blend mandate, carbon tax) is evaluated. All studies provide results for both the Home region and the ROW region.

Table 1
Overview of studies about the rebound effect of biofuel consumption.
Sources: see Table.

Source	Modelling approach	Scenario/experiment	Time frame	Geographic scope
Rajagopal et al. [11]	A relatively simple two regions (US and ROW) Partial Equilibrium (PE) model of the global oil market is used.	Two scenarios are considered related to the US Renewable Fuel Standard (RFS2): (1) with the RFS2 and (2) without the RFS2. An obligatory 7.5% market share of corn ethanol in US transport fuel in 2015 on domestic and world fuel price, consumption and GHG emissions. Imports of biofuels are assumed to be uncompetitive with US biofuel production due to import tariffs.	2015	USA, ROW
Thompson et al. [18]	A PE model of the oil and oil product markets is used that is linked to an agriculture and biofuels model.	Three scenarios are considered related to the US Renewable Fuel Standard (RFS2), including biodiesel from vegetable oils and ethanol from corn and sugar cane: (1) a baseline scenario with an extension of the biofuel use mandate, tax credits and ethanol tariff, (2) a scenario 1 in which tax credits and ethanol import tariff are discontinued from 2011, and (3) a scenario 2 in which the biofuel mandate is terminated from 2011, but the tax credit and ethanol tariff are continued. Three assumptions are included about the extent to which biofuel consumption in the US replaces foreign biofuel consumption: 100%, 50% and 0%.	2010–2020	USA, ROW
Drabik and De Gorter [16]	PE modelling framework of oil and oil product markets model, combined with an agriculture and biofuels model	Three scenarios are considered based on the US Renewable Fuel Standard (RFS2) biofuel policies in the US for the year 2009 taking into account only corn ethanol: (1) scenario 1 considers a 10% blend mandate, (2) scenario 2 is a tax credit of 0.52 $ per gallon of ethanol and (3) scenario 3 applies to both a blending mandate and a tax credit. The blending mandate considers 3 possible premiums for a binding mandate: 0.00, 0.14 and 0.34 $ per gallon. An autarky scenario is also considered which approximates a scenario where all countries adopt biofuel policies.	2009	USA, ROW
Taheripour and Tyner [17]	Computable General Equilibrium (CGE) model GTAP-BIO-ADV to quantify the economic impacts of US ethanol policy.	Three scenarios are considered related to the US Renewable Fuel Standard (RFS2): scenario 1 finances the mandate through gasoline production tax. Scenario 2 finances it through a gasoline production tax and by a reduction in agricultural subsidies to zero. Scenario 3 finances through an income tax and a reduction in agricultural subsidies to zero.	2004–2015	USA, ROW
Chen et al. [20]	PE Biofuel and Environmental Policy Analysis Model (BEPAM).	A reference scenario is included which assumes no biofuel policy. Three scenarios are considered relative to the baseline: scenario 1 assumes a US Renewable Fuel Standard (RFS2) mandate following the Annual Energy Outlook (AEO) projections of the US Energy Information Administration (EIA). Scenario 2 assumes a mandate and volumetric tax credits, which is discontinued in 2012. Scenario 3 assumes an RFS mandate as well as a carbon price Instrument in which a carbon tax varies over time from 20 $ to 39 $ per ton CO_2 equivalents in 2010 and 2022 respectively.	2007–2022	USA, ROW
Stoft [31]	Simple model with only an oil demand and supply equation, parameterised using results from global climate and energy models.	The California Low Carbon Fuel Standard (LCFS) is considered which requires 10% reduction in carbon content of fuels used in California. Rebound effects are however calculated using global average oil supply and demand elasticities.	2009	World
Hochman et al. [12]	Cartel of Nations (CON) PE model, which is an extension of the optimal export tax model. An oil exporting region (OPEC) and an oil importing region (ROW) are considered.	Two scenarios are considered: (1) a reference scenario without biofuel production in ROW countries and (2) a scenario with biofuel production in ROW countries. Biofuel production and consumption in OPEC countries is assumed to be zero. Four levels of oil price demand elasticity are considered.	2007	OPEC, ROW
Laborde [19]	The CGE model MIRAGE (Modeling International Relationships in Applied General Equilibrium)-Biof.	EU biofuels consumption in the baseline scenario is kept at the 3.3% blending ratio of 2008. The biofuel scenario assumes biofuel use of the National Renewable Energy Action Plans of the 27 member states (total biofuel consumption) reaches 8.6% of the mandated target of 10%.	2008–2020	EU, ROW

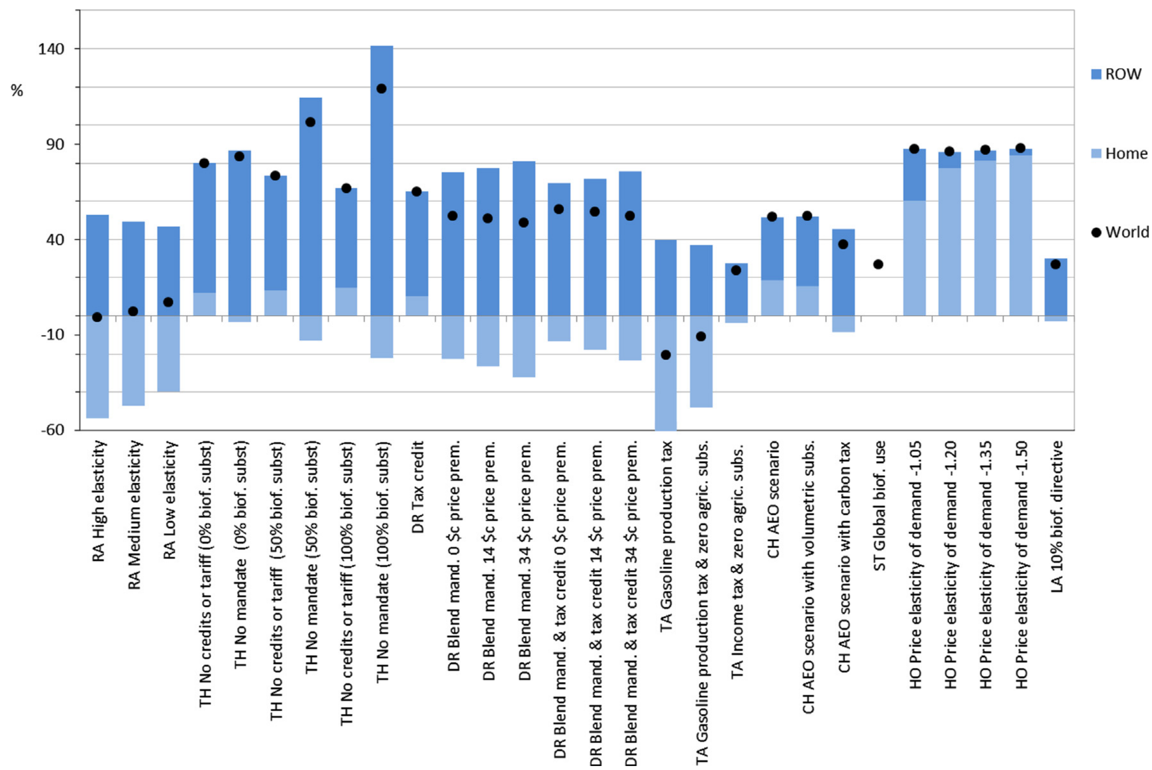

Fig. 2. Overview of the rebound effects as projected in the eight reviewed studies.
Sources: RA = Rajagopal et al. [11], TH = Thompson et al. [18], DR = Drabik and De Gorter [16], TA = Taheripour and Tyner [17], CH = Chen et al. [20], ST = Stoft [31], HO = Hochman et al. [12], LA = Laborde [19].

3.2. *The rebound effects in the eight reviewed studies*

Estimates of the rebound effect vary widely, from −20% to 119%, depending on, among others, the assumed parameters used for calculating the rebound effect and the biofuel policy (Fig. 2). The following sections will further explain the results.

3.3. *Biofuel policies and their consequences for rebound effects*

3.3.1. *Biofuel blend mandates*

Most studies reviewed consider the RFS2 biofuel policies in the US. Until recently, the RFS2 included a biofuel blending mandate and subsidies (tax credits) for biofuel producers and ethanol import tariffs. In this paragraph we focus on the impact of a blend mandate. The obligatory mixing of biofuel with conventional fuel in the US increases the price of (mixed) fuel in the US, as biofuels are typically more costly than conventional fuel. For example, Rajagopal et al. [11] estimated that the mandatory use of ethanol in the US increases the price of fuel by 5.4–6.4%, depending on the assumed oil supply and demand elasticities. Consumers are forced to take the price of blended transport fuel as given and respond by consuming less fuel. This results in negative rebound effects in the Home region (US), i.e. the consumption of gasoline decreases more than the use of biofuel (on energy basis) in Rajagopal et al. [11], Drabik and De Gorter [16], Taheripour and Tyner [17], Thompson et al. [18]. Also Laborde [19] predicts a 3% negative rebound effects in the Home region (EU) as a result of the biofuel blend mandate in the RED. These negative rebounds effects partially counteract the positive rebound effect in the ROW, where gasoline and oil prices go down (due to excess supply as demand in the Home region reduces); consequently the use of gasoline goes up.

The studies referred to above focus on the impact of the use of first-generation biofuels. Chen et al. [20] also considered the use of second generation biofuel from lignocellulose biomass in the US till 2022. They find that, assuming a reduction in processing costs, the production of lignocellulose biofuel becomes increasingly competitive. This reduces the use of costly first generation biofuels and leads to a reduction of the price of fuel in the US. This explains the positive rebound effect in the Home region (US) by 17%.

3.3.2. *Biofuel subsidies and tax exemptions*

Drabik and De Gorter [16] compared the impact of three different scenarios of biofuel policies on world fuel and gasoline consumption: a tax credit, a blend mandate and a combination of the blend mandate and the tax credit. The global rebound effect is significantly higher under a tax credit policy (65%) than under a mandate (49–52%; see Fig. 2), because tax credits reduce the mixed fuel price and hence stimulate the use of biofuels with consequently lower demand for gasoline in the Home country. This leads to a lower price for gasoline at the international market which again increases the demand and use of it in ROW. This result is emphasised by the scenario in which the two policies (tax credit and a blending mandate) are combined, producing a higher rebound effect (52–56%) than under the blending mandate, but a lower rebound effect than the 65% rebound effect in case of a tax credit only. Drabik and De Gorter also considered the impact of ethanol price premiums over the tax credit: 0.00, 0.14 and 0.34 $ per gallon. A zero price premium means that the mandate alone results in the same ethanol price as the tax credit alone. The higher the price premium, the more negative the rebound effect in the US and the more positive the rebound effect in the ROW, whereas their simulations estimate slightly lower global net effect in case of higher US ethanol price premiums (Fig. 2). Thompson et al. [18] came to similar conclusions. Chen et al. [20] predict that a biofuel mandate with volumetric tax credits for corn ethanol and lignocellulose biofuel especially increases the production of lignocellulose biofuel due to the higher tax credit for lignocellulose biofuel

compared to corn ethanol. The effect of the volumetric tax credits is a lower (negative) rebound effect in the US, a higher (positive) rebound effect in the ROW, but the global rebound effect is nearly unaltered.

3.3.3. Carbon tax

Chen et al. [20] evaluate the impact of a carbon or gasoline tax with a biofuel blend mandate. Chen and colleagues show that a carbon or gasoline tax reduces consumption of high-carbon fuels and results in a movement towards second-generation biofuels and away from gasoline consumption. The domestic rebound effect is negative as a result of the increase in price of fuel, i.e. gasoline consumption is reduced more than the increase in biofuel consumption. The decrease in gasoline consumption is partly compensated by the higher use of gasoline in the ROW (i.e. the higher rebound effect in the ROW). The net effect is that the global rebound effect is lower compared to the other two scenarios that are considered by Chen et al. (Fig. 2).

3.4. Interactions with other policies

The CGE studies of Taheripour and Tyner [17] and of Laborde [19] show that interactions of financial biofuel promoting policies and other taxes can substantially affect the rebound effects of biofuel policies. Taheripour and Tyner [17] show that the rebound effect is strongly influenced by how a biofuel production subsidy is financed. An increase of the tax on gasoline production to finance the ethanol production subsidy reduces the domestic consumption of the blended fuel, since consumers cannot choose between gasoline and biofuels and can only buy the blended fuel. This results in a strong negative domestic and global rebound effects (−60% and −21%, respectively). In the second experiment agricultural subsidies are reduced to zero, plus a limited increase of the tax on gasoline production is assumed to cover the remaining costs of the biofuel production subsidy policy. The rationale behind the decrease in agricultural subsidies is that in the US agricultural subsidies are linked to the price of agricultural commodities and biofuel policies have raised the price of agricultural commodities and hence reduced the need for agricultural subsidies. This scenario results in a lower increase of the price of the blended fuel and in a −48% domestic and −11% global rebound effects (Fig. 2). In the third scenario a similar reduction of agricultural subsidies as in the second scenario is assumed, in combination with an increase in income tax. This has the effect that the burden of the ethanol production subsidy is spread across all economic activities and this limits the rebound effect to −4% domestically and 24% globally. In the CGE modelling study of Laborde [19], consumers pay the higher costs of mandatory use of biofuels as subsidies or tax credits are not explicitly considered. None of the other studies explicitly consider the fact that biofuel policies and other taxes interact and that these interactions affect the rebound effects of biofuel policies.

3.5. Biofuel trade

The reviewed studies differ in the way trade in biofuels is included: some do (Thompson et al. [18]; Chen et al. [20,19], others do not (Rajagopal et al. [11], Drabik and De Gorter [16] and Hochman et al. [12]).

Thomson et al. [18] investigated the effects of eliminating different elements of US biofuel support on the composition of fuels used in the US and in the rest of the world. Their study specifically focuses on the consequences of discontinuity of tax credits and the ethanol import tariff. Results are highly context specific, and very sensitive to whether or not the mandates are binding. For instance, as long as there is no binding mandate that restricts responses, more sugar-cane ethanol is imported if there is no tariff. This may affect foreign ethanol prices and use, depending on ethanol producers' responses to greater US ethanol net imports. More ethanol imports for the US can lead to lower biofuel consumption in the rest of the world, foreign consumers who no longer buy turning to gasoline, effectively increasing the rebound effect of US biofuel policy. In discussing their results the authors point at the impact of the selected international supply and demand elasticities which they call a key uncertainty in their representation of fuel markets. The authors conclude that the complexity of biofuel policies and the interactions of gasoline, diesel and biofuel markets need further investigation to better evaluate environmental effects of biofuel policies.

3.6. Elasticity of substitution between gasoline and biofuel

In most of the models used in the reviewed studies, the supply of biofuels is derived from assumptions that biofuels and fossil fuels are perfect substitutes and that a profit maximising producer chooses the cheapest combination of these products given their prices. The Constant Elasticity of Substitution (CES) function is mostly chosen to govern this process. The use of constant elasticities of substitution underestimates the rebound effect of biofuel when substitution of fossil fuel by biofuel becomes increasingly difficult, but overestimates the rebound effect when substitution of fossil fuel by biofuel becomes easier, e.g. when flex fuel vehicles are being used. The magnitude of these biases is probably limited in the case of the current situation in the EU and the US, as biofuels are usually not sold separately and consumers are thus forced to take the price of blended transport fuel as given. Moreover, also the (limited) timeframe of biofuel policies of the EU and the US limits the biases in the estimated rebound effects when assuming constant elasticities of substitution.

The PE Biofuel and Environmental Policy Analysis Model (BEPAM) applied by Chen et al. [20] does not use the approach described above. It derives the demand for alternative fuels from technical and logistic constraints and limits, such as the ethanol blend wall (i.e. the use of ethanol in conventional car engines is limited to 10% of the fuel on energy basis). In this way, the use of constant elasticities of substation is avoided.

3.7. Price elasticities of demand and supply

There is common agreement in the literature about the importance and sensitivity of the rebound effect depending on the assumed price elasticities of especially the demand and supply of gasoline or oil. A higher price elasticity of fuel demand magnifies the impact of biofuel use on oil consumption and thus also the rebound effects. A higher price elasticity of oil supply decreases the rebound effects. Rajagopal et al. [11] explicitly investigate the impact of oil supply and oil demand elasticities on the rebound effect of biofuel use in the Home region (US) and on the ROW. The authors assume three sets of oil supply and oil demand price elasticities, namely 0.25, 0.20 and 0.15 for oil supply in the US and 0.40, 0.35 and 0.30 in the ROW and the same (negative) values for oil demand in the US and ROW. These elasticities are chosen to be representative for a timeframe of 5 years. Decline in the oil consumption in the US is stronger in the high elasticity case, but at the same time the oil consumption increase in the ROW is higher. Consequently the rebound effect in the US is more negative, whereas the rebound effect in the ROW is more positive and the global rebound effect is lower compared to the low elasticity experiment (Fig. 2). The sensitivity analyses conducted by Chen et al. [20] show that with a lower supply elasticity of gasoline in the ROW (0.05 instead of 0.20) the gasoline

Table 2
Price demand and price supply elasticities of gasoline or oil consumption used in the various studies dealing with rebound effects of biofuels.*Sources*: see Table.

	Time-frame	Geographic scope	Price elasticity of gasoline or oil demand		Price elasticity of gasoline or oil supply		Rebound effects		
			USA or non-OPEC	ROW or OPEC	USA or non-OPEC	ROW or OPEC	USA or non-OPEC (%)	ROW (%)	World (%)
Thompson et al. [18]	2020	USA, ROW	n/d	−0.35	n/d	0.35	−22 to 15	52 to 141	67 to 119
Hochman et al. [12]	2007	OPEC, ROW	−0.10	−1.05 −1.20 −1.35	n/a	0.10	61 to 84	4 to 27	86 to 88
Rajagopal et al. [11]	2015	USA, ROW	−0.15 −0.20 −0.25	−0.30 −0.35 −0.40	0.15 0.20 0.15	0.30 0.35 0.40	−40 to −54	−47 to −53	−1 to 7
Drabik and De Gorter [16]	2009	USA, ROW	−0.26	−0.40	0.20	0.20	−32 to 10	55 to 81	49 to 65
Chen et al.	2022	USA, ROW	−0.20	−0.26	0.049	0.20	−8 to 19	33 to 46	37 to 52

price declines stronger, which results in a larger domestic and international rebound effect. Important thereby is the relatively low oil price of 35 US$ per barrel that is assumed. A higher price of oil results in more elastic supply curves and higher rebound effects; see Table 2 for the range of elasticities used in the studies reviewed in this paper.

Except Hochman et al. [12], the assumed price elasticities of demand in the US range between −0.10 and −0.26 and for the ROW between −0.26 and −0.40. The elasticities of oil and gasoline supply range from 0.05 to 0.40. The differences in assumed demand elasticities are partially the result of differences in the timeframe considered. Drabik and De Gorter [16] investigate short term effects and assume a relatively high price elasticity of demand for the ROW (−0.40). Thompson et al. [18], Chen et al. [20] and to a lesser extent Rajagopal et al. [11] look at longer-term effects (up to 2022) and assume lower price elasticities of demand. Further, Hochman et al. [12] find that higher biofuel use yields more elastic demand functions as domestic consumers become less dependent on oil (through a decrease of their oil consumption share). The biofuel use in the reviewed studies varies between 0.95 EJ in Taheripour and Tyner [17] and 2.70 EJ in Rajagopal et al. [11], which may explain part of the difference in calculated rebound effects.

Further, Chen and co-workers assume a relatively small price elasticity of gasoline or oil supply for the ROW (0.20), which has an upward effect on the rebound effect, compared to Thompson et al. [18] and Rajagopal et al. [11]. In the latter two studies long-term supply elasticities of 0.30–0.40 are considered, which suggest that there are viable alternatives to oil production in 2020, or else the rebound effects would be (even) higher than the 67–119% global rebound effect projected by Thompson and colleagues.

Finally, none of the studies specifically addressed the potential impact of the imperfect oil price-reversibility mechanism, i.e. that demand for oil responds asymmetrically to oil price changes. Gately and Huntington [21] find that the price elasticities are significantly different across price falls and price increases and that an increase in the oil price reduces oil demand, but a decline in oil demand is not necessarily reversed by a decrease in the oil price, which would reduce the significance of the rebound effect.

3.8. Oil supply responses to increased biofuel use

The results above show that the response of oil supply to the use of biofuels is among the most important and uncertain aspects that influence the rebound effect. Several theories about oil supply are relevant here, which are discussed below but which are only partially covered in the studies reviewed in this paper. These theories have to do with the position and behaviour of the OPEC at the oil market.

Crucial in the responses at the oil supply side to biofuel policies might be the behaviour of the OPEC as a dominant supplier of crude oil in the world. Hochman et al.'s study [12] is the only study using a oligopolistic market (Cartel-of-Nations (CON)) model to simulate impact of biofuel policies on the oil market, and compares results of the CON model with a model in which competitive behaviour is assumed for all oil-exporting countries. The authors find that the decline in the gasoline consumption is much higher in the CON model projection compared with the competitive model. This implies that oil producers acting in an oligopolistic market would adjust supply downwards in order to accommodate the decrease in gasoline demand, i.e. OPEC responds to the introduction of biofuels by decreasing gasoline production beyond the level predicted by the perfect competition model to mitigate the decline in oil price. This reduces the rebound effect, although the net total global rebound effects are however not necessarily low due to assumptions on oil demand elasticities. Hochman and colleagues assume relatively high (−1.05 to −1.35) price elasticities of oil demand for OPEC countries and a relatively low value for non-OPEC countries (−0.10) (Table 2). The Home rebound effect is calculated by Hochman and colleagues in the range of 61–84% and the ROW rebound effect is in the range of 4–27%, resulting in a large global rebound effect that varies between 86% and 88%. Note that the results of Hochman et al. are only partially relevant for biofuel use in the EU and US, as they assume a competitive biofuel industry, which explains the positive rebound effect in the ROW.

A key assumption in Hochman et al. [12] is that OPEC responds to a reduction in oil demand by limiting oil export (which explains the high rebound effect in non-OPEC countries that consume biofuel) and by stimulating domestic oil consumption (which causes a limited rebound effect in ROW/OPEC countries). Ramcharran [23] estimated oil supply functions for oil producers (OPEC and non-OPEC) using data for the period 1973–1997, which included phases of both rising and falling prices. For the OPEC members, the results support the target revenue theory, which states that the objective of oil-exporting countries is to meet certain target revenue over a period of time. This theory also postulates that oil production is reduced in response to rising oil prices and increased with declining prices, i.e. a negative price elasticity of supply. The target revenue theory suggests that even higher rebound effects are feasible compared to studies reviewed in this article.

Another theory that results in negative oil supply elasticities is the green paradox, which was first proposed by Sinn. The green paradox is the theory that climate change and other

environmental protection policies act like an incentive for owners of oil and other fossil fuel resources to shift their production toward the present. Van der Ploeg and Withagen [25] investigated this phenomenon and found that subsidising relatively expensive renewable energies results in increased depletion of oil and gas: in anticipation of mid- and long-term future decreases in demand for oil, producers are incentivised to increase extraction in the short-term future. Based on the green paradox the rebound effects would be higher compared to the ranges found in the literature reviewed here.

4. Modelling the rebound effect with MAGNET

We now turn to own estimations of rebound effects of the EU RED, using the simulation tool MAGNET, which is the acronym for Modular Applied GeNeral Equilibrium Tool, (until 2010 referred to as LEITAP). MAGNET is a global computable general equilibrium model that covers the global economy. MAGNET is based on the Global Trade Analyses Project (GTAP) model, which is developed at Purdue University in the United States [26]. To model biofuel use and conventional fuel production in the MAGNET CGE model, we adapt the nested Constant Elasticity of Substitution (CES) function of the GTAP-E model [27] and extend it for the petrol sector. We include intermediate input nests in the petrol sector to introduce the substitution possibility between crude oil, ethanol and biodiesel. The nested CES structure implies that biofuel demand is determined by the relative prices of crude oil versus ethanol and biodiesel, including taxes and subsidies. A detailed description of the (default) version of MAGNET that is used in this study can be found in Woltjer et al. [28].

We model the use of biofuel in the EU in MAGNET by means of a biofuel blend mandate as specified in the Renewable Energy Directive (RED). The RED aims at reaching a 10% share of renewable fuels in transport fuel use in 2020. It should be mentioned that this mandatory blending is budget-neutral from a government point of view. To achieve this in a CGE model involves implementing two policies. First, the biofuel share of transport fuel is specified and made exogenous such that it can be set at a certain target. An endogenous biofuel subsidy is modelled to achieve the required biofuel share. Second, to ensure that this incentive instrument is budget-neutral, the biofuels subsidy is financed by an end-user tax on petrol consumption, implying that the petrol user pays for the cost involved for using biofuel. This is in line with reality, although in some countries tax exemptions for biofuel are implemented. The rebound effect of biofuel use in the EU is calculated considering the model parameter values identified in the literature review (see Section 3.7 and below). This is done based on the range of model parameter values identified in the literature review, whereby also other relevant studies for example oil supply is considered. In this way, the sensitivity of rebound effects with respect to selected model parameters and scenario assumptions is investigated. In particular, we test responsiveness of rebound effects for

- fuel price elasticity of households demand in the EU, which is a highly uncertain parameter varying between −0.10 and −1.35 in the reviewed studies (Table 2),
- price elasticity of substitution between biofuels and fossil base fuels (as in Rajagopal et al. [11]), and
- biofuel mandate level to validate the results of Hochman et al. [12] who found higher rebound effects for higher biofuel mandates.

We did not test the responsiveness of the rebound effect for oil price supply elasticities, since in MAGNET oil supply is demand driven so it is not explicitly driven by oil price and supply elasticities.

To test sensitivity of the rebound effect on these assumptions, we run the following six scenarios:

(1) Reference Scenario with key features:
  (a) 10% Biofuel blend mandate in the EU.
  (b) Oil price elasticity of households demand in the EU of −0.756.
  (c) Elasticity of substitution between biofuels and fossil base of value 3.
(2) Low Demand Elasticity Scenario: as Reference Scenario but with fuel price elasticity of households demand of −0.150 (changes assumption b of the Reference Scenario)
(3) High Demand Elasticity Scenario: as Reference Scenario but with fuel price elasticity of households demand of −1.350 (changes assumption b of the Reference Scenario)
(4) High Fuels Substitution Elasticity Scenario: as Reference Scenario but with a substitution elasticity between biofuels and fossil base fuels of value 5.
(5) Low Biofuel Mandate Scenario: as Reference Scenario but 5% biofuel mandate in the EU.
(6) High Biofuel Mandate Scenario: as Reference Scenario but 20% biofuel mandate in the EU.

All scenario experiments are implemented on the top of macroeconomic and technological development projections and run for the 2007–2020 time period. The initial 2007 data set is 2007 GTAP database, macroeconomic and population development come from the USDA's Economic Research Service (ERS) and exogenous agricultural yields growth as expected by FAO [29]. To identify the impact biofuel mandates scenarios with and without the RED biofuel mandate in the EU are used.

By comparing results of Scenarios 2–6 with the Reference Scenario (Scenario 1), we assess the impact of selected model parameters and scenario assumptions on the rebound effect. Implementation of the RED directive in the EU in MAGNET leads to an increase of biofuel use and a decrease of demand for oil. Consequently, the world market price of biofuel increases and the price of crude oil decreases, resulting in a decrease in the price of blended fuel. This decrease of blended biofuel price induces additional demand for crude oil and results in a positive global rebound effect, i.e. the decrease in oil consumption is less than the biofuel production increase. Next to this price induced rebound effect an additional rebound effect is induced by changes in income. The demand for biofuel and consequently agricultural commodities results in an increase in GDP outside the EU. This in turn leads to an additional demand for fuel and a positive rebound effect in the ROW. In EU, on the other hand, GDP decreases, which contributes to the price-induced negative rebound effect.

In the Reference Scenario (Scenario 1), the global rebound effects of biofuel use for the EU, ROW and world are −23%, 47% and 24%, respectively (see Table 3). A lower (higher) oil blended fuel price elasticity of demand in Scenario 2 (and Scenario 3, respectively) results in smaller (larger) changes in fuel consumption in the EU compared to the Reference Scenario as consumers respond weaker

Table 3
Rebound effects (%) in the MAGNET scenario experiments.*Source*: Author's calculations with MAGNET model.

Rebound effects (%)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Home (EU)	−23	−22	−24	−19	−10	−27
ROW	47	44	48	50	44	44
WORLD	24	22	24	30	34	17

(stronger) on the increase of blended fuel price. To compare with the Reference Scenario, the result is a less negative (more negative) rebound effect in the EU, which is counteracted by a lower (higher) positive rebound effect in the ROW.

In Scenario 4 we assume that technological and logistical constraints make it easier to increase biofuel use in comparison with Reference Scenario. Consequently the biofuels price does not increase as much as in Reference Scenario, which leads to a lower EU consumer price of blended fuel and consequently higher demand for fuel. Scenario 4 leads to less GDP losses compared with the Reference Scenario, and also to a higher demand for fuel. These two effects result in higher EU and global rebound effects; the latter increases from 24% (in the Reference Scenario) to 30%.

Scenarios 5 and 6 consider a change in the 10% blending mandate required in the RED to respectively 5% and to 20%. This significantly affects the rebound effect in EU while the ROW rebound remains almost unaltered. With a 5% mandate the biofuel policy is less restrictive and the rebound effect is influenced in a similar way as in Scenario 4. This leads to an increase of the rebound effect compared with the Reference Scenario (from −23% to −10% for the EU and worldwide from 24% to 34%). The higher biofuel mandate has opposite effects and leads to lower rebound effects compared with the Reference Scenario.

The results in Table 3 show that the rebound effects of biofuel use are caused by both income effects and by oil price effects. In general, implementing the biofuel mandate results in income losses in the EU and income gains in the ROW. The latter leads to an increase in demand for fuel in ROW and induces an increase of the rebound effect. The results also show that more ambitious biofuel mandates decrease the rebound effect. However, when technical limits of using biofuels blending are reached, the substitution of fossil fuels by biofuels will be more difficult. A shift to new technologies (such as flex–fuel vehicles) will be required. In case this is not happening such a scenario can be seen as one opposite to Scenario 4, with consequently lower rebound effects compared with those in the Reference scenario.

5. Impact of biofuel use in the EU 27 on the global GHG emissions

In this section we evaluate the impact of the rebound effect of first-generation biofuel use in the EU 27 on global GHG emissions. As Laborde [19] and the MAGNET analyses are the only two studies specifically investigated the rebound effects of the biofuel blend mandate in the EU, we concentrate on their results when evaluating the impact of the rebound effect on GHG emissions. In addition we also include calculations of GHG emission savings referring to rebound effects estimated by some of the other reviewed studies.

Table 4
The GHG emissions of bioethanol and biodiesel fuels used in the EU 27 in the year 2020 (as % of fossil fuel emissions). *Sources*: Laborde [19] and author's calculations.

	Feedstock	Emissions from biofuel production	Emissions from ILUC	Emissions from biofuel production and ILUC
Ethanol	Wheat	37	16	53
Ethanol	Maize	36	11	47
Ethanol	Sugar beet	30	8	38
Ethanol	Sugar cane	22	14	36
Biodiesel	Palm fruit	36	60	96
Biodiesel	Soy beans	50	62	112
Biodiesel	Sunflower	36	58	94
Biodiesel	Rapeseed	45	60	105
Biofuel mix	Average mix	37	42	79

The impact of the rebound effect on GHG emissions is expressed per net unit of fossil fuel replaced. This is done using data on GHG emissions of production of biofuels and of Indirect Land Use Change (ILUC) from the 'No change in trade regime' scenario in the study of Laborde [19]:

- The GHG emissions of production of biofuels used in the EU are calculated based on Life Cycle Assessments (LCA) and take into account the impact of improved technology in 2020. Data are given for the different types of biofuel used in the EU and for the average biofuel mix used in the EU (see Table 4, column 3).
- The GHG emissions of ILUC are estimated by Laborde ([19]; see Table 4, column 4). Laborde's study has also been used to calculate the ILUC emissions of biofuels in the proposal for amendment of the RED [6].

The GHG emissions of conventional gasoline and diesel are 90 g CO_2 equivalents per MJ [19]. The emissions of biofuel production and ILUC vary per biofuel type and feedstock. The GHG emissions of biofuel production of the weighted mix of biofuels used in the EU in 2020 are equivalent to 37% of the emissions of conventional fuels, whereas ILUC emissions add another 42% (Table 3, columns 3 and 4). This means that the GHG emissions of biofuel use in the EU in 2020 are 79% of the emissions of conventional fuel, excluding rebound effects. In other words, the average GHG saving of biofuel use in the EU is 21% (column 6 in Table 4). Next, the total net GHG saving of biofuels is calculated by correcting these results for the rebound effect, i.e. more than one unit of biofuel production is needed per unit fossil fuel (on energy basis), because one unit of biofuel does not replace one unit of fossil fuel. In other words, the GHG saving per net unit of fossil fuel replaced is thus the sum of the GHG emissions of production of biofuels plus the GHG emissions of ILUC divided by $(100–RE_{WRLD}) \times 0.01$.

Next, we consider the results of the two studies that specifically investigate the rebound effect of biofuel use in the EU. Laborde [19] estimates the global rebound effect at 30%. Applying the formula above, the emissions of the EU biofuel mix are then 102 gCO_2 eq. per MJ replaced (Fig. 3). This is a 13% higher GHG emission compared to conventional fossil fuels and 42% higher (the top part of the second, third and fourth bar) than the emissions of biofuel use when only the emissions of production and ILUC are considered (the). Our own estimates of the rebound effect of biofuel use in the EU range from 22% to 34%, which is dependent on the choice of model parameters and assuming a 5–10% biofuel blend mandate (hence, excluding scenario 6 that is based on a 20% biofuel mandate). A 22% global rebound effect results in 91 gCO_2 eq. per MJ biofuel, i.e. an increase of just

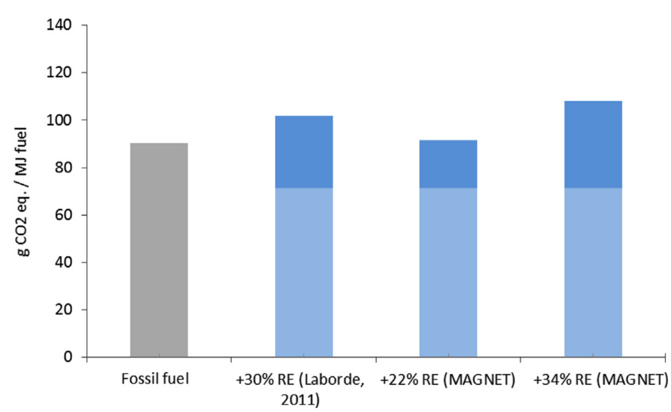

Fig. 3. The impact of the rebound effect of biofuel use in the EU 27 on GHG emissions (in gCO_2 eq./MJ fuel).
Sources: MAGNET/author's calculations and Laborde [19].

1 gCO_2 eq. per MJ replaced fossil fuel (Fig. 3). A 34% rebound effect, on the other hand, leads to 108 gCO_2 eq. per MJ biofuel, or 20% more than 90 gCO_2 eq. per MJ when using conventional fuel.

For the purpose of reference we also consider the GHG emissions savings of biofuels based on the rebound effect calculations from some of the studies reviewed in Section 3. If, for instance, we assume the −1% rebound effect from Rajagopal [11] that would be applicable to the EU situation, than the GHG emission saving of biofuel use which would increase 1%-point, to 22%. Taking the 88% rebound effect estimated by Hochman et al. [12] in case of a competitive biofuel industry and assuming the OPEC cartel controls oil supply, the use of biofuel in the EU leads to a total of 594 gCO_2 eq. per MJ (incl. ILUC emissions), which is 6–7 times higher than the emissions of conventional fuel.

6. Discussion and conclusions

In this paper, eight studies about the rebound effect of biofuel use have been reviewed and in addition the MAGNET CGE model has been used to evaluate the sensitivity of the rebound effect of biofuel use in the EU. Results differ due to differences in approaches, models and their parameters used to quantify the economic mechanisms causing the rebound effect, the geographic scope, the timeframe and the biofuel policy regime. Perhaps most important yet little researched in this context is the behaviour of the OPEC as major oil supplier in the world. Modelling oil supply in general, and the role of OPEC, is complex and a number of, partially contradictory, empirical and theoretical considerations should be addressed. For example, the OPEC Target Revenue and Green Paradox theory suggest negative price elasticity of oil supply, i.e. oil production increases when oil prices decline. This would lead to higher rebound effects than the values predicted by the reviewed studies and by the MAGNET CGE model. More factors are potentially relevant (such as the assumption of constant returns to scale), but the impact of these factors has not been investigated in the reviewed studies.

The policy implications of the rebound effect can be far-reaching. The rebound effect in the biofuel producing region is usually negative, which means that biofuels are effective in reducing domestic GHG emissions and increase energy security. However, the positive rebound effect in the Rest Of the World (ROW) results in a (positive) net global rebound effect. Further, the use of second generation biofuels is promoted in the EU Renewable Energy Directive (RED) to avoid negative impacts on food security and biodiversity and emissions from ILUC. Second generation biofuels are also frequently mentioned as a cheaper alternative to first-generation biofuels if more efficient technologies become available. However, a shift from costly first-generation biofuels to cheaper biofuel also means higher rebound effects, which may partially undo the reduction in ILUC emissions.

The rebound effect can be counteracted by, for example, a carbon tax on oil consumption, a GHG emission trading system, or by limiting subsidies to biofuel production and use. Further, important is that the analyses of GHG emissions ignore the impacts on other energy markets. Especially relevant thereby are the impacts on gas markets, as the price of gas is strongly correlated with the price of oil, but also the impacts on the use of coal and on renewable energy technologies are potentially important.

The rebound effect is also important for the macro-economic impacts of biofuel policies in terms of effects on, e.g. welfare, GDP, employment and trade balance. The rebound effect determines to what extent production of biofuel is an additional economic activity or an activity that replaces oil production or import of oil. Gehlhar et al. [30] found that if biofuel production technology advances and oil prices continue to rise as projected and exceed the break-even price, then the RFS2 biofuel policy in the US could benefit the US economy. The GDP would increase, household consumption rise (because of higher real wages) and prices of import would decrease. Substituting domestic biofuels for oil imports implies less imports overall and increases the price of exports, resulting in a favourable impact in terms of trade. Similar effects apply to other large bioenergy producers, like the EU and Brazil. Improved technology and increased investments increase the potential positive effects of biofuel production for economic growth. Also Taheripour and Tyner [17] investigated the welfare effects of the RFS2 in the US and the relevance of including costs of biofuel policies.

We conclude that the review and analyses presented in this paper clearly show that the rebound effects of biofuel use can greatly decrease the GHG saving potential of biofuels, even more than ILUC, and point at the need for detailed economic modelling when evaluating the environmental sustainability, the effectiveness of biofuel promoting policies, but also the economic impacts.

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